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HYBRID ELECTRIC-LASER PROPULSION SYSTEM AND ASSOCIATED METHODS

Background

[0001] Discussions of micro-propulsion technology that are currently available for use on spacecraft may be found in Micci, M. M., and Ketsdever, A. D., "Micropropulsion For Small Spacecraft", American Institute of Aeronautics and Astronautics, Inc., Virginia, 2000 and Leach, R., and Neal, K. L., "Discussion of Micro-Newton Thruster Requirements For a Drag-Free Control System", Proceedings of the 16th AIAA/Utah State University Conference on Small Satellites, Logan, UT, August 2002, each of which are incorporated herein by reference.

[0002] The increasing demand in science and military applications for precision orbital positioning and formation flying platforms has created a need for enabling technologies and systems.

[0003] Electric and laser-type thrusters are forms of micro-propulsion technologies/mechanisms that utilize two different means of converting (electric/laser) energy into exhaust kinetic energy, to generate a force. Various forms of electric propulsion technology (e.g. Pulsed Plasma Thrusters (PPT), Hall thrusters, Field Emission Electric Propulsion (FEEP) and Colloid thrusters) have been researched since the early 1950's, while research into laser type thrusters for use in space applications has been researched since the early 1970's. For further information regarding the designs and operation of these micro-propulsion technologies, attention is directed to the following publications: Burton, R.L. and Turchi, P.J., "Pulsed Plasma Thruster", Journal of Propulsion and Power, Vol. 14, No. 5, September 1998, Hoskins, W.A., Wilson, M.J., Willey, M.J., Meckel, N.J., Campbell, M. and Chung, S. "PPT Development Efforts at Primex Aerospace Company", AIAA 99-2291, Marcuccio, S., Genovese, A. and Andrenucci, M., " Experimental Performance of Field Emission Microthrusters", Journal of Propulsion an d Power, Vol. 14, No. 5, October 1998, Saccoccia, G., and Berry, G., "European Development and Applications of Electric Propulsion Systems", Proceedings of the 50th International Astronautical Congress, Amsterdam, The Netherlands, October

[0004] 1999, Pranajaya, F., "Colloid Micro-Thruster Experiment", Design Document, Stanford University, 2000 and Stephenson, R. R., "Electric Propulsion Development and Application in the United States", International Electric Propulsion Conference IEPC Paper 95-1, September 1995, each of which is incorporated herein by reference.

[0005] Major limiting factors in current micro-thrusters are repeatability, inefficiency in propellant and power usage, low specific impulse (I_{sp}), contamination, and the inability to operate in a continuous (i.e. low noise) operating mode.

[0006] Preceding patents illustrative of the prior art include: U.S. Patent No. 6,530,212, to C. R. Phipps et al., entitled "Laser Plasma Thruster"; U.S. Patent No. 4,866,929, to S. Knowles et al., entitled "Hybrid Electrothermal/Electromagnetic Arcjet Thruster and Thrust Producing Method";U.S. Patent No. 5,170,623, to C. L. Dailey et al., entitled "Hybrid Chemical/Electromagnetic Propulsion System"; and U.S. Patent No. 6,318,069, to L. R. Falce et al., entitled "Ion Thruster having grids made of oriented Pyrolytic Graphite".

Summary Of The Invention

[0007] In one embodiment, a system constructed according to the teachings herein provides high efficiency, low noise, micro-/milli-Newton thrust range propulsion that may be utilized within applications across the broad range of low and high-Earth orbital platforms, including a wide range of platform masses and missions from small satellites to nano-satellites. In certain embodiments, the system may be employed to achieve a range of capabilities, such as: fine impulse control, high specific impulse, low noise, high mission ΔV, maximum thrust for minimum power, minimum contamination and maximum lifetime.

[0008] In one embodiment hereof, a hybrid electric-laser propulsion ("HELP") system combines features of electric and laser-type thrusters into a single thruster unit, as described below. The system may create a repeatable plasma by utilizing a propellant with rapid self-regenerative surface morphology qualities, coupled with application of an extremely high-powered short-pulse laser, to better collimate the trajectory of the exhaust plasma with the application of an electric/electromagnetic field. The system may also be used on an electric-only basis. In certain applications, the

system provides a stable, scalable and non-interfering (reduced noise and contamination) propulsion system with I_{sp}'s up to about 1000,000 seconds and an integrated ΔV up to 10000 $m.s^{-1}$ (which is up to a factor of 1000 greater than prior art). An added advantage of the system's impulse resource assists telescopic systems which desire longer dwell times on target as they can be operated to perform continual de-saturation of its momentum wheels, as well as aid with the pointing stability and provide larger satellites with longer life precision positioning. The HELP system's higher total impulse resource may also be used to provide small satellites with capability of changing plane and/or orbit.

[0009] The thrust mechanism of the HELP system may also repeatably employ nearly 100% of its propellant, obtaining an efficiency greater than prior art electric and laser type micro-thrusters; it may also have reduced weight, cost and power consumption, increase mission lifetime and decrease volume because the propellant is stored in a solid form, as compared to the prior art.

[0010] In one embodiment, the HELP system is modular and scaleable in design, which enables the system to be tailored to application and mission-system constraints. Multiple, modular HELP thrusters may thus be combined to create a larger system with a greater thrust operation range. In one embodiment, multiple lasers are combined into a single unit to create a unit with higher mass flow and, thereby, thrust.

Brief Description Of The Figures

[0011] FIG. 1 shows a block diagram of one HELP thruster system

[0012] FIG. 2 shows one possible configuration of the components of the HELP thruster system of FIG.1

[0013] FIG. 3 shows a flowchart of the sub-processes associated with the HELP thruster system

[0014] FIG. 4 shows a cross-sectional view of one thruster illustrating one configuration for the system of FIG. 1.

[0015] FIG. 5 illustrates one multi-thruster HELP thruster system.

[0016] FIG. 6 illustrates various parameter regimes in laser processing.

[0017] FIG. 7 shows a flowchart illustrating interaction and feedback associated with laser ablation.

[0018] FIG. 8 shows a diagram portraying certain effects that result from laser exposure.

[0019] FIG. 9 illustrates a laser-light intensity regime where plasma shielding arises.

[0020] FIG. 10 illustrates the LSCW regime.

[0021] FIG. 11 illustrates how a material's surface structure is impacted after being ablated by laser radiation.

[0022] FIG. 12 shows a flowchart illustrating one process for placing a propellant into a 'ready to ablate' state for use within a HELP thruster system.

[0023] FIG. 13 shows a diagram that depicts a configuration of a passively q-switched laser.

[0024] FIG. 14 shows a flowchart illustrating one process for initializing and placing a laser into a 'ready to ablate' state for use within a HELP thruster system.

[0025] FIG. 15 shows a flowchart illustrating one process for initializing and operating an exhaust plume vectoring field for use within a HELP thruster system.

[0026] FIG. 16 shows a flowchart illustrating steps for determining HELP thruster system operation per mission criteria.

[0027] FIG. 17 shows a flowchart summarizing steps involved for controlling one thruster in a HELP thruster system.

[0028] FIG. 18 shows an example of a 12x6 thruster transformation matrix **M** used by the thruster control strategy process of FIG. 17.

[0029] FIG. 19 shows an example of a 6x6 Degree of Freedom thrust transformation matrix **A** used by the thruster control strategy process of FIG. 17.

[0030] FIG. 20 shows an example of a 12x6 –ve thruster transformation matrix **C**, in terms of negative thrust components and degrees of freedom, used by the thruster control strategy process of FIG. 17.

[0031] FIG. 21 shows an example of a 12x6 +ve thruster transformation matrix **B**, in terms of positive thrust components and degrees of freedom, used by the thruster control strategy process of FIG. 17.

[0032] FIG. 22 shows an example of a 12x6 thruster transformation matrix **X** used by the thruster control strategy process of FIG. 17.

[0033] FIG. 23 shows a flowchart illustrating steps for controlling a thruster within a multi-thruster HELP thruster system.

[0034] FIG. 24 shows a flowchart illustrating steps for determining HELP thruster system configuration and propellant choice per mission criteria.

Reference Numerals in Drawings

[0035] FIG. 2

12 Low Voltage DC Power Supply Unit
14 High-Powered Short-Pulse Laser
16 Fiber Optics for Diode Pump
18 Microchip and Q-Switch
20 High repetition output laser beam
22 Ablation Target Section of the propellant
24 Replaceable Propellant Pod/Cartridge
26 Propellant Heater
28 Propellant Housing
30 Temperature Sensors
32 Exhaust Plasma Jet (⊥ to surface)
34 Exhaust Plume Vectoring Field
36 Thrust Vector

[0036] FIG. 4

14 & 18 Microchip and Q-Switched Laser
16 Fiber Optics for Diode Pump
20 High repetition output laser beam
22 Ablation Target Section of the propellant
24 Replaceable Propellant Pod/Cartridge
26 Propellant Heaters
28 Propellant Housing
30 Temperature Sensors
34 Exhaust Plume Vectoring Field
36 Thrust Vector
38 Plug-and-Play Fiber Optics Connector
40 Laser Contamination Baffle
42 Propellant
44 Lightweight Structure and Thermal Shield
46 Plug-and-Play Electrical Connector
48 Exit Throat Chamber

[0037] FIG. 5

20 High repetition output laser beam
28 Propellant Housing
40 Laser Contamination Baffle
44 Lightweight Structure and Thermal Shield

DETAILED DESCRIPTION OF THE INVENTION

[0038] FIG. 1 & 2 show one HELP system **110** (FIG. 1 shows block components of system **110**, FIG. 2 shows thruster operation of system **110**). In FIG. 2, system **110** is shown with a propellant **24** and laser **14 & 18** that cooperate to generate a plasma **32**. Laser **14 & 18**. Specifically, system **110** has a low power diode-pumped solid-state laser **14**, complementing fiber optics **16**, Q-switch and microchip **18** (see FIG. 13), an exhaust plume vectoring field **34**, target propellant pod **24** and housing **28**. For system **110**, a propellant **24** with high surface tension (e.g., having a value ≥ 50 dyne/cm) and low vapor pressure (e.g., having a value ≤ 10 kPa) when in a semi-molten state is desired so that it has rapid self-regenerative surface morphology properties, which is required for enabling repeatability. In one example, propellant **24** is Paraffin.

[0039] The low power diode-pumped solid-state laser beam at 808 nm wavelength is carried through fiber optics **16** to the Q-switch and microchip **18**. The microchip consists of a monolithic block of either Nd:YAG or Nd:YVO4 coupled with a Cr^{4+}:YAG saturable absorber (see FIG. 13). The Nd atoms are excited by the 808 nm pump and lase at 1.06 microns. The output **20** is an intense high repetition rate pulsed laser beam that is directly focused onto the regenerative ablation target surface of the propellant **24**. The action of focusing the laser beam **20** onto the ablation target section of the propellant **24** results in the production of a highly ionized plasma jet **32**, which provides thrust **36**. An electric/electromagnetic field (the *exhaust plume-vectoring field* E_v) **34** is used to control and collimate the trajectory of ions **32** expelled from the target propellant **24**. This focuses the plasma **32** vector trajectory and improves the achievable specific impulse and thrust, as well as minimizing contamination and cross-coupling effects. Nonetheless a contamination baffle housing **40** (see HELP system **120**, FIG. 4) may surround the laser so as to protect it from stray ions or particulates **32** that may release upon ablation of the target propellant **24**, as a preventative measure to minimize deterioration of the laser performance.

[0040] Certain functional capabilities of system **110** may be summarized by three sub-processes of laser ablation, propellant supply and the exhaust plume collimation. The first sub-process entails maintaining the propellant **24** in a semi-molten state, while the latter two sub-processes involve operating and controlling lasers **14 & 18**

and collimating electric/electromagnetic field **34** respectively (see, e.g., FIG. 3, which shows a flowchart of these sub-processes associated with the HELP thruster system).

[0041] FIG. 4 shows one HELP system **120** , suitable for use as system **110**. A hexagonal tubular lightweight assembly **44** provides the core structure for HELP thruster system **120**, onto which all other thruster components are attached or are contained. The construction of the lightweight structure **44** also forms an 'exit throat chamber' **48** and thermal shielding and control.

[0042] FIG. 5 shows a multiple-configuration HELP system **130**. In FIG. 5, the modular design of the HELP thruster system (FIG. 4) is used multiple times within larger system **130**, sized to accommodate the application. One exemplary use of system **130** is to provide propulsion for plane or orbit changes and precision maneuvers for a wide selection of spacecraft ranging from large satellites to nano-satellites.

[0043] The process of laser ablation (i.e. material removal via laser-light) is complex involving different processes depending on how the laser-light interacts with the target matter causing varying effects (FIG. 6 gives an overview of the various parameter regimes in laser processing). The principal processes that are responsible for the onset of ablation are 'photochemical', 'photothermal' and 'photophysical.' FIG.7 shows a flowchart illustrating some of the different interaction and feedback mechanisms involved in laser ablation. Ablation via the photochemical process, for example, involves the breakdown of the chemical bonds in the molecule, while photoablation involves heating of the material and photophysical refers to a combination of both photochemical and photothermal processes. In a process termed 'mechanical,' which refers to laser-light induced volume changes, stresses and defects arising in the material can also result in ablation. The interaction mechanism that results between the laser-light and the target material is dependent on both the parameters of the laser beam (e.g., pulse width, fluence, wavelength of laser-light, intensity, and width of laser focus, etc.) and the physical and chemical properties of the target material (e.g., bulk elemental composition, melting- and boiling-points, reflectivity, and particle size, etc.). Typically the excitation energy from the laser-light is dissipated into heat; thus photothermal is the process assumed to occur and dominant to cause the ablation. The dominant effects that result from laser exposure

include laser-induced 'melting', 'vaporization' and 'plasma formation', and are defined by the laser-light intensity (see FIG. 8 and FIG. 6).

[0044] With regard to the application of laser ablation in the HELP thruster system **110**, as material is removed to form plasma **32**, energy is released at high velocities producing specific impulses I_{sp}. There are three different dynamic behavior regimes associated with plasma formation: 'laser-supported combustion waves (LSCW)', 'laser-supported detonation waves (LSDW)' and 'superdetonation', all of which are dependent upon the laser-light intensity. The wavelength of the laser-light can also impact how a laser interacts with a material. Fore example, if the laser-light intensity reaches a critical value, typically 10^7 W/cm^2 < I_{cr} < 10^{10} W/cm^2, and depending on the laser-light wavelength, plasma shielding (FIG. 9) can also arise; that is, the laser-light does not reach the substrate but instead is completely absorbed by the plasma **32**, resulting in weak coupling between the plasma and the substrate and inhibiting energy transfer (i.e., laser-induced material vaporization stops). The first regime is that where LSCWs occur, specifically where the laser-light intensity I is high enough to cause optical breakdown within the gas/vapor in front of the substrate, but where it is too low to cause a detonation wave (i.e. $I_p \leq I \leq I_d$). Under this circumstance, plasma **32** remains stationary and is confined to a region near the surface (see FIG. 10) unless the intensity increases, in which case plasma plume **32** expands away from the target material. The second regime involves higher laser-light intensities, specifically $I \geq I_d$, where $I_d > 10^8$ W/cm^2; here, the ablated material propagating away with supersonic speeds generates a shock wave that drives both the ambient medium and the substrate. In this case, the velocity of the shock wave in the ambient is approximately equal to that of the ionization front. The propagation velocity of a LSDW v_{dw} can be approximated by

$$v_{dw} \approx \left(2(\gamma^2 - 1)\frac{I}{\rho_g} \right)^{1/3} \propto I^{1/3},$$

where γ is the adiabatic coefficient $\approx 5/3$, and ρ_g is the density of the ambient medium. The third regime involves high laser light intensities, typically $I \geq 10^9$ W/cm^2, where superdetonation arises. Under this condition, the ionization front propagates in front of the shock wave. The propagation velocity of superdetonated ionization waves v_{sd} can be described by

$$v_{sd} \propto I^{n},$$

where n >1, and values for v_{sd} have been shown to reach values on the order of 10^9 cm/s; I_{sp}'s up to 1000,000 seconds can be achieved.

[0045] However, the process of laser ablation inherently results in thrust repeatability issues. Previous laser ablation experiments have demonstrated this and result from a change in the target's surface morphology with repeated exposure to a pulsed laser. The surface morphology of substances exposed to a laser can vary dramatically and often result in a rough trough burned into the target material surface after a period of time (see FIG. 11). Consequently, avoiding re-exposure of the target propellant's surface **22** ensures repeatability in a thruster system that utilizes the process of laser ablation. System **110**, FIG. 1, solves this repeatability issue by continually forming a virgin surface before repeated laser exposure, accomplished by utilizing the propellant's **24** natural surface tension. Specifically, within the HELP thruster system **110**, a propellant **24** is used with rapid self-regenerative surface morphology. The propellant **24** is stored in a solid form, and then heated so that its surface converts to a semi-molten state; thus its surface tension will naturally and continually reform a new smooth surface layer. The target propellant section **22** can be re-exposed to the laser to produce a repeatable thrust level with reduced propellant waste, enabling approximately 100% usage of propellant **24** and minimizing dead weight (and with no moving parts). The desired characteristics of propellant **24** are a high surface tension, low melting temperature and low vapor pressure. An example of a propellant **24** that has these qualities is Paraffin; other materials that have the desired properties can also be used. The propellant pod **24** will be contained within a protective housing **28** to minimize exposure to the space environment (vacuum) so as to minimize the loss of propellant **24** via vaporization because this can also be a major source of propellant **24** use inefficiency.

[0046] The task of maintaining the propellant **24** in a molten state with adequate surface tension, while being laser illuminated and exposed to the space environment, is facilitated by use of a control algorithm (see FIG. 12, FIG. 14, FIG. 16, FIG. 17) in conjunction with appropriately sensitive thermostats **30** and precision heaters **26** (FIG. 1, FIG. 2). See in particular FIG. 12, which shows a flowchart illustrating a process for placing a propellant into a 'ready to ablate' state and maintaining it in a semi-molten state during operation of the HELP thruster system).

[0047] The utilization of Q-switched lasers in commercial applications has become very popular due to excellent beam quality and increased peak pulse power over traditional gas lasers. These qualities are also very desirable to the HELP thruster system **110**, since more energy per pulse can be transferred to the plasma **32** resulting in increased plasma **32** velocity, which translates to increased specific impulse (I_{sp}) and mission ΔV capability.

[0048] The technique of passive Q-switching involves the use of a saturable absorber within the laser cavity to delay the onset of lasing. Specifically the laser pump energy is accumulated within the absorber material until it reaches the materials saturation point (most of the atoms/molecules are in a high-energy state), at which point the absorber material becomes bleached and transparent to the incident light and then emits a short high-energy laser pulse. FIG. 13 shows the basic configuration of a passively Q-switched laser.

[0049] The HELP thruster system **110** may be operated in either a pulsed or pseudo-steady-state continuous mode. The pseudo-steady-state continuous mode is achieved by operating the passively Q-switched microchip laser **14** & **18** at high repetition rate (10-100 kHz) compared to the satellite system response resonances. Those skilled in the art appreciate that other lasers with like specifications may also be employed in HELP thruster system **110** without departing from the scope hereof.

[0050] In one embodiment, the HELP thruster system **110** employs passively Q-switched Nd:YAG microchip laser **14** & **18** to produce very short pulse widths (< 218 ps) and very high peak powers (≥ 565 kW), which is up to 50 times greater than produced by conventional Q-switched lasers. The laser design is therefore inherently robust and reliable; it may also be packaged into very small volumes ($\leq 7e^{-5}$ cm^3 laser system is currently available from Uniphase) making it an economical choice over other lasers. Other features of such lasers include reported electrical efficiency (≥ 35%) and high mean-time-between-failure (MTBF) of 1 million hours (~ 114 years).

[0051] Short pulse widths are desirable as they reduce the heat-affected zone, which in turn reduces the collateral damage that results on the target propellant **22**, minimizing the work involved in replenishing the surface. The high intensity is also ideal to maximize HELP thruster system's **110** specific impulse (I_{sp}) and mission ΔV

capability, since plasma 32 velocity is proportional to the laser-light intensity. FIG. 14 shows a flowchart illustrating initializing a laser to place it into a 'ready to ablate' state during operation of one HELP thruster system.

[0052] FIG. 15 shows a flowchart illustrating one process for initializing and operating an exhaust plume vectoring field for use within a HELP thruster system.

[0053] FIG. 16 shows a flowchart illustrating steps for determining HELP thruster system operation per mission criteria.

[0054] FIG. 17 and FIG. 23 show flowcharts summarizing principal steps of the singular and multiple ganged thruster unit control strategies, respectively, that can be utilized with the operation of the HELP thruster system. FIG. 18 to FIG. 22 show examples of various transformation matrices that may be developed and utilized by the aforementioned control strategies (in the case where four clusters of three thrusters spaced equally apart are mounted at the midpoint around the circumference of a cylindrical spacecraft body – where the configuration of thrusters within each cluster are arranged axisymmetrically around the clusters main axis, at a 70° angle from the normal to the cylinder surface such that the thrusters in each cluster are separated from each other by an angle of 109°). The transformation matrices utilized by the multiple thruster control strategy may be developed in a similar manner to those for the singular thruster control strategy, the main difference being they involve an extra magnitude multiplier that accounts for the number of additional thrusters that are incorporated and aligned together (as the ganging intuitively would increase the various thrust components magnitudes).

[0055] FIG. 24 shows a flowchart illustrating steps for determining HELP thruster system configuration and propellant choice per mission criteria.

[0056] Appendix A contains, for disclosure purposes, certain non-limiting support material to better understanding the HELP system.

CLAIMS

What is claimed is:

1. A hybrid electric-laser thruster system, comprising:

a propellant having a self-regenerative surface morphology property;

a laser for ablating the propellant to create an ionized plasma jet that is non-interfering with a trajectory path of expelled ions;

a baffle for protecting the laser from contaminants released when the propellant is ablated;

an electromagnetic field generator for generating an electromagnetic field to define a thrust vector from the jet.

2. The system of claim 1, further comprising capillary feed means for replenishing the propellant.

3. The system of claim 2, the capillary feed means comprising utilizing surface tension of semi-molten propellant.

4. The system of claim 1, further comprising a propellant housing for protecting the propellant from environmental factors.

5. The system of claim 4, further comprising one or more propellant heaters for heating a surface of the propellant such that the surface is in a semi-molten state, wherein propellant surface tension continually reforms the surface.

6. The system of claim 5, further comprising one or more propellant temperature sensors for monitoring temperature of the propellant to ensure that the propellant is not overheated but is maintained at the necessary temperature so as to maintain the propellant in a semi-molten state at the surface.

7. The system of claim 6, further comprising a housing for containing the replaceable propellant module and for mechanical coupling with the sensors, heaters, baffle, generator and laser, to form a modular unit.

8. A hybrid electric-laser thruster system, comprising:

a plurality of modular thruster units coupled together to provide cooperative thrust, each of the units having:

a propellant having a self-regenerative surface morphology property;

a laser for ablating the propellant to create an ionized plasma jet that is non-interfering with a trajectory path of expelled ions;

a baffle for protecting the laser from contaminants released when the propellant is ablated;

an electromagnetic field generator for generating an electromagnetic field to enhance definition of a thrust vector from the jet.

9. The system of claim 8, each unit further comprising capillary feed means for replenishing the propellant.

10. The system of claim 9, the capillary feed means comprising utilizing surface tension of semi-molten propellant.

11. The system of claim 8, each unit further comprising a propellant housing for protecting the propellant from environmental factors.

12. The system of claim 11, each unit further comprising one or more propellant heaters for heating a surface of the propellant such that the surface is in a semi-molten state, wherein propellant surface tension continually reforms the surface.

13. The system of claim 12, each unit further comprising one or more propellant temperature sensors for monitoring temperature of the propellant to ensure that the propellant is not overheated but is maintained at the necessary temperature so as to maintain the propellant in a semi-molten state at the surface.

14. The system of claim 13, each unit further comprising a housing for containing its replaceable propellant module and mechanically coupling with its sensors, heaters, baffle, generator and laser, to form a modular unit.

15. The system of claim 8, further comprising interlocking fixtures to connect the multiple units together.

16. The system of claim 8, further comprising fiber optic and electrical connectors for 'plug-and-play' supply of power.

17. The system of claim 1 or 7, propellant comprising a wax-based material.

18. The system of claim 17, the wax-based material comprising Paraffin.

19. A method of providing thrust propulsion to a spacecraft, comprising:

pulsing laser energy onto a propellant having a self-regenerative surface morphology to ablate the surface and form ionized plasma; and

generating an electromagnetic field to collimate trajectory of the plasma to provide the thrust.

20. The method of claim 19, the propellant comprising a wax-based material.

21. The method of claim 20, the wax-based material comprising Paraffin.

22. The method of claim 19, further comprising dynamically controlling the thrust.

23. The method of claim 22, the step of controlling comprising setting an operating regime to one of LSCW, LSCD or superdetonation.

24. The method of claim 19, further comprising selecting thruster operation process, thruster components and configuration, and propellant as a function of mission.

25. A method of providing thrust propulsion to a spacecraft, comprising:

pulsing a plurality of lasers onto a like plurality of propellants, each propellant having a self-regenerative surface morphology to ablate the surface and form ionized plasma; and

generating a like plurality of electromagnetic fields to collimate trajectory of each plasma to provide the thrust.

110

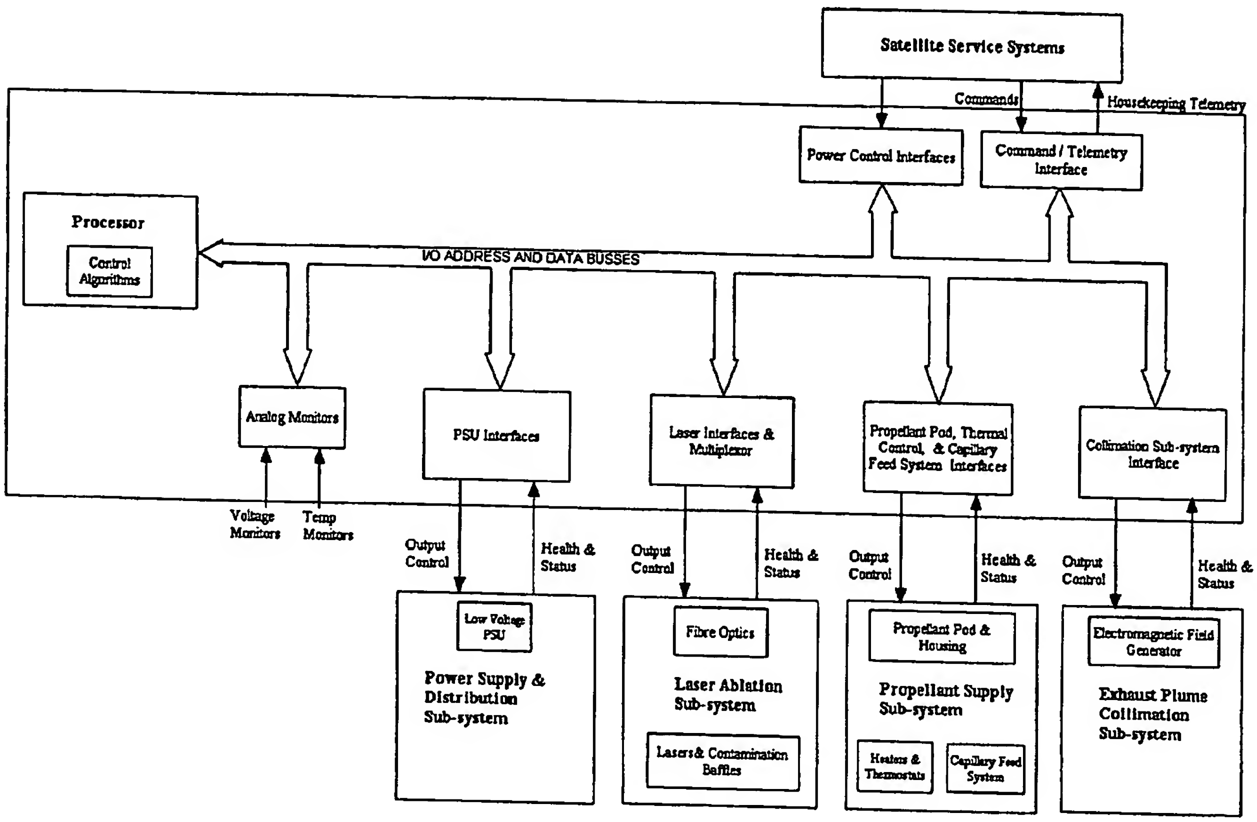


Figure 1 " Block Diagram of Hybrid Electric-Laser Propulsion (HELP) System Components"

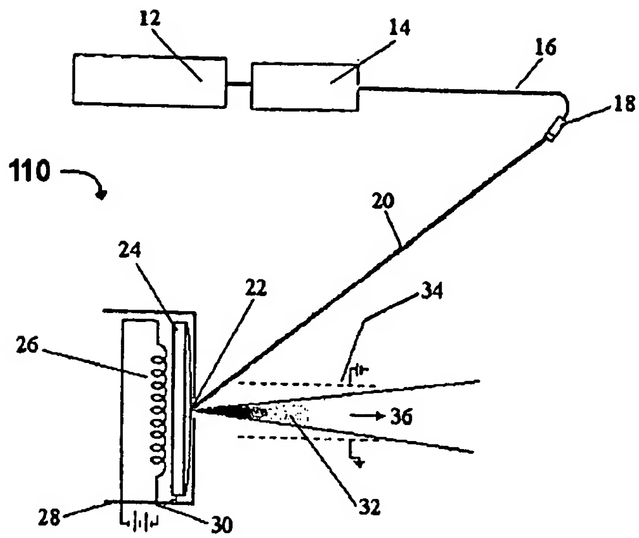
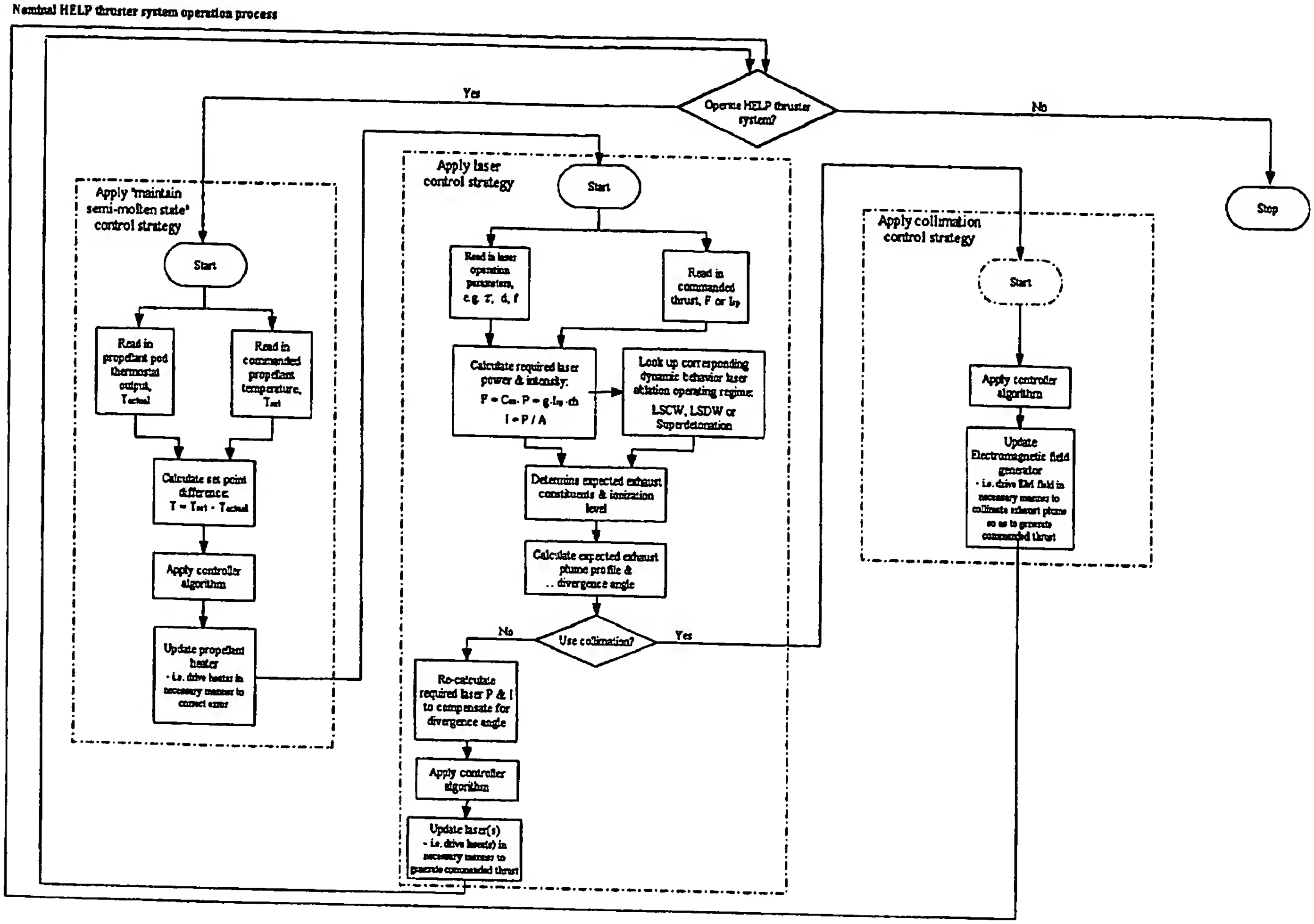


Figure 2 "Hybrid Electric-Laser Propulsion (HELP) System Baseline Flight Design Components"

Nominal HELP thruster system operation process



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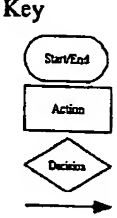


Symbol denoting the start or end
Symbol denoting an action
Symbol denoting a decision
Symbol denoting flow direction

Figure 3 "Flowchart illustrating the principal sub-processes involved when operating the HELP thruster system"

"Singular System"

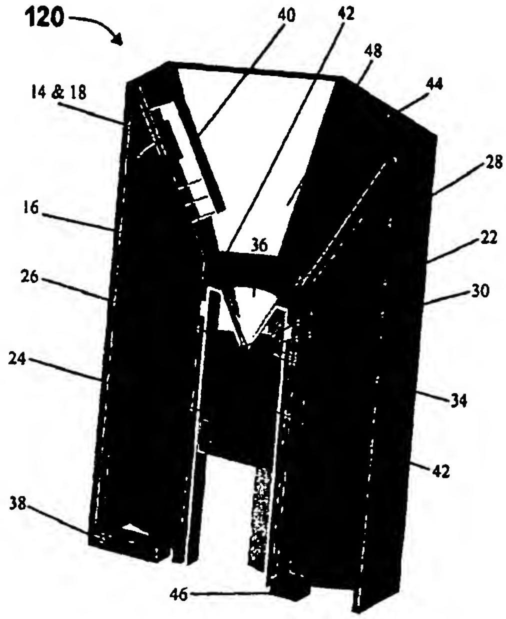


Figure 4 "Cross-section of Hybrid Electric-Laser Propulsion System Baseline Flight Design"

"Multiple Configuration System"

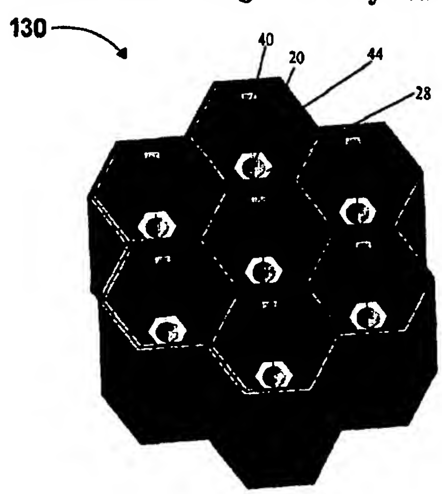


Figure 5 "Hybrid Electric-Laser Propulsion System Baseline Flight Design"

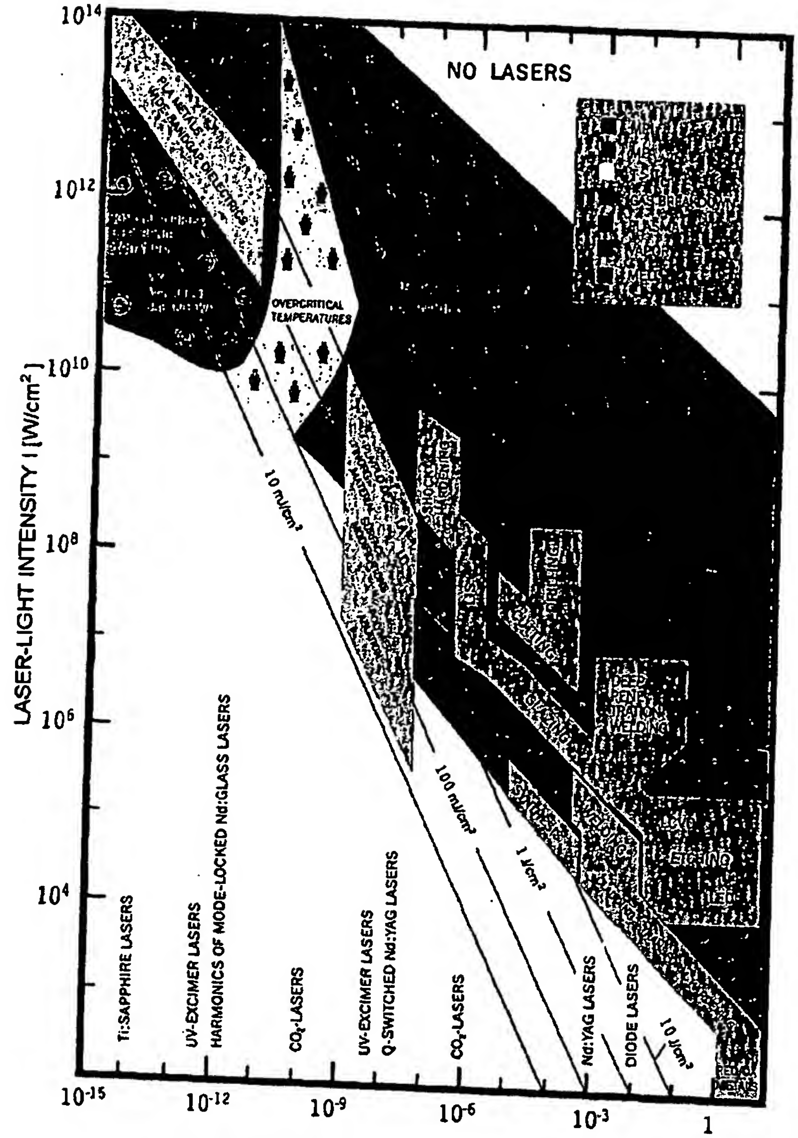
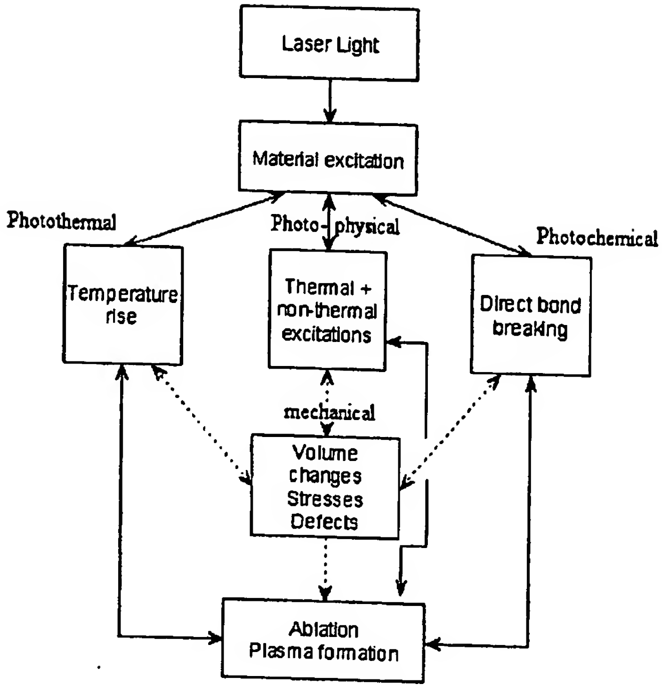


Figure 6 "Overview of the various parameter regimes in laser processing"



Key

⟶ Solid arrows indicate direct paths resulting in ablation
- - → Dashed arrows indicate indirect paths resulting in ablation
⟷ Double-headed arrows indicates coupling between processes

Figure 7 "Flowchart illustrating some of the different interaction and feedback mechanisms that can be involved in laser ablation"

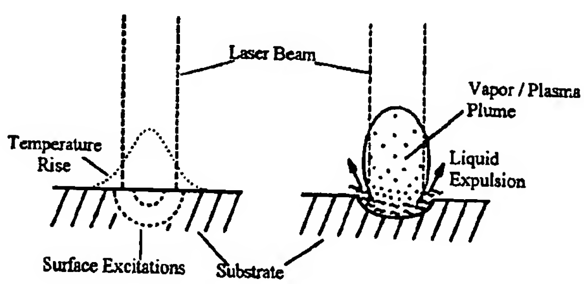


Figure 8 "Illustration depicting the dominant effects that result from laser exposure i.e. laser-induced *melting*, *vaporization* and *plasma formation*"

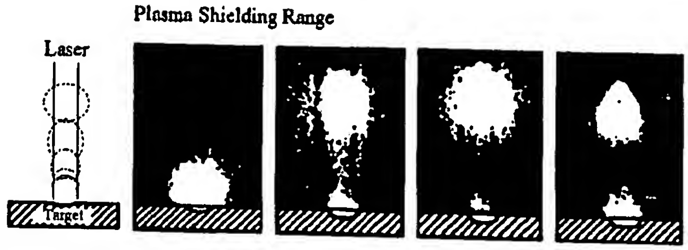


Figure 9 "Critical laser-light intensity range where Plasma shielding arises"

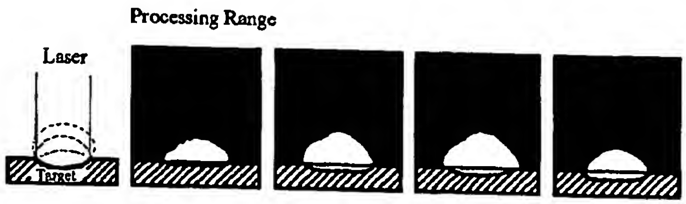


Figure 10 "LSCW regime where the laser-light intensity is high enough to create a stationary plasma in front of the substrate, which is confined to region near the surface"

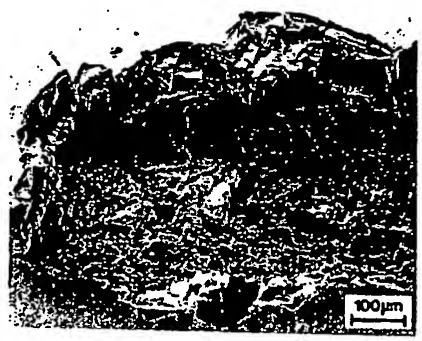
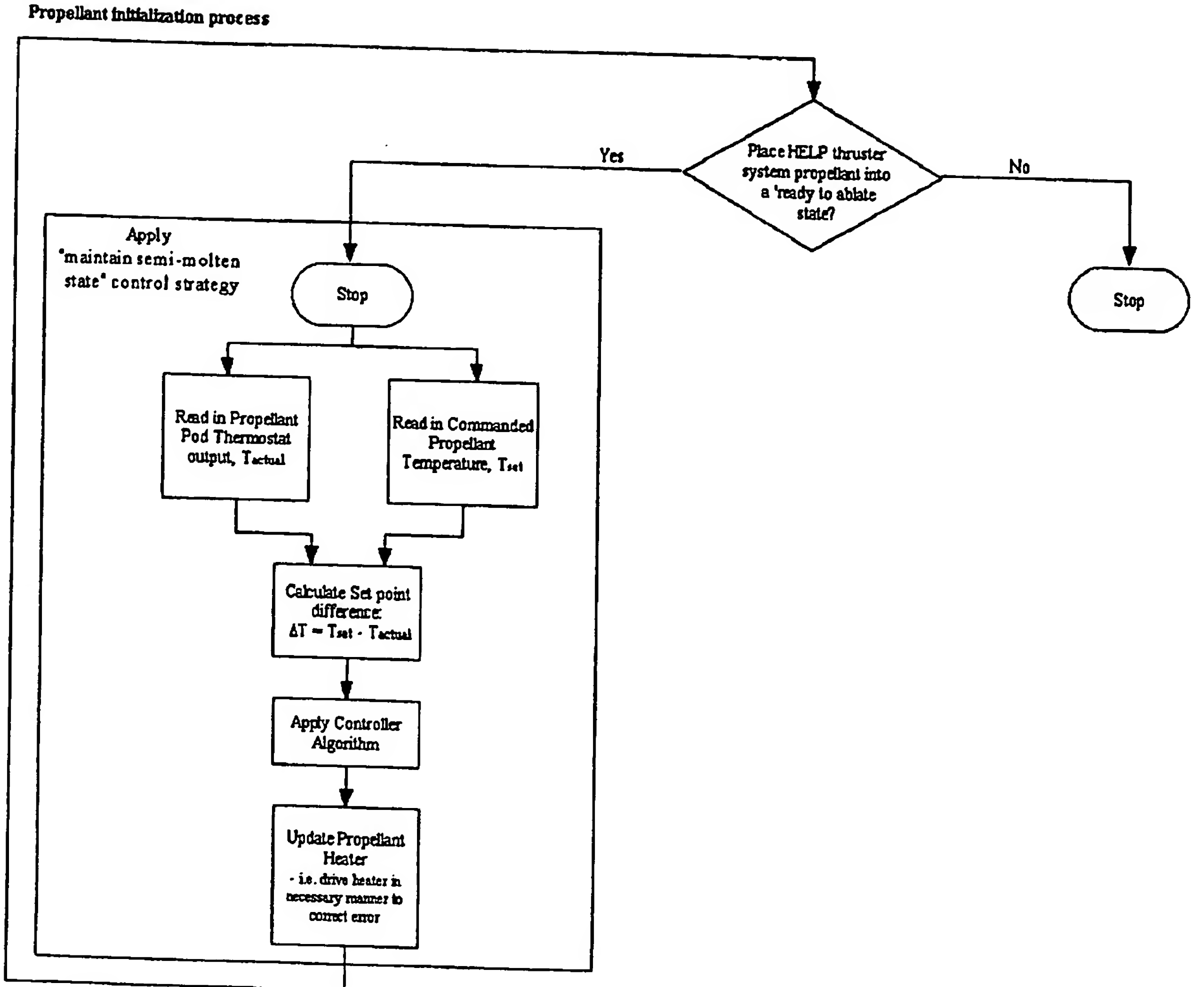
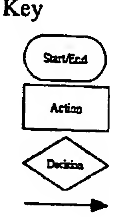


Figure 11 "Example of how a materials surface structure is impacted after being ablated by laser radiation"



Key



Symbol denoting the start or end

Symbol denoting an action

Symbol denoting a decision

Symbol denoting flow direction

Figure 12 "Flowchart illustrating the process involved to place a propellant into a 'ready to ablate' state for use within the HELP thruster system"

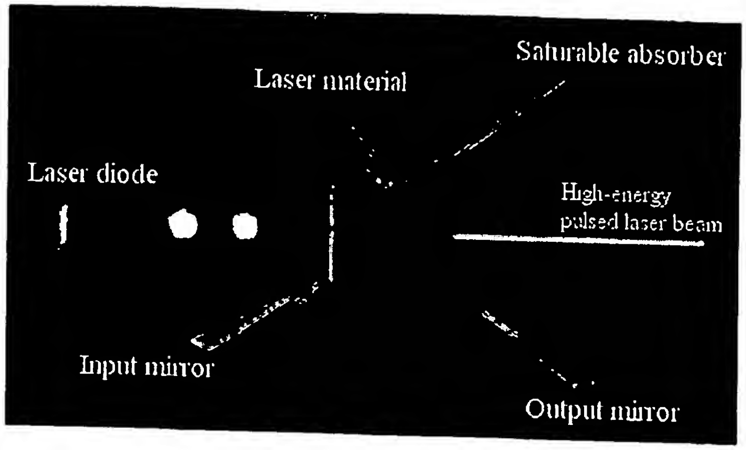


Figure 13 "Basic configuration of a passively Q-switched laser"

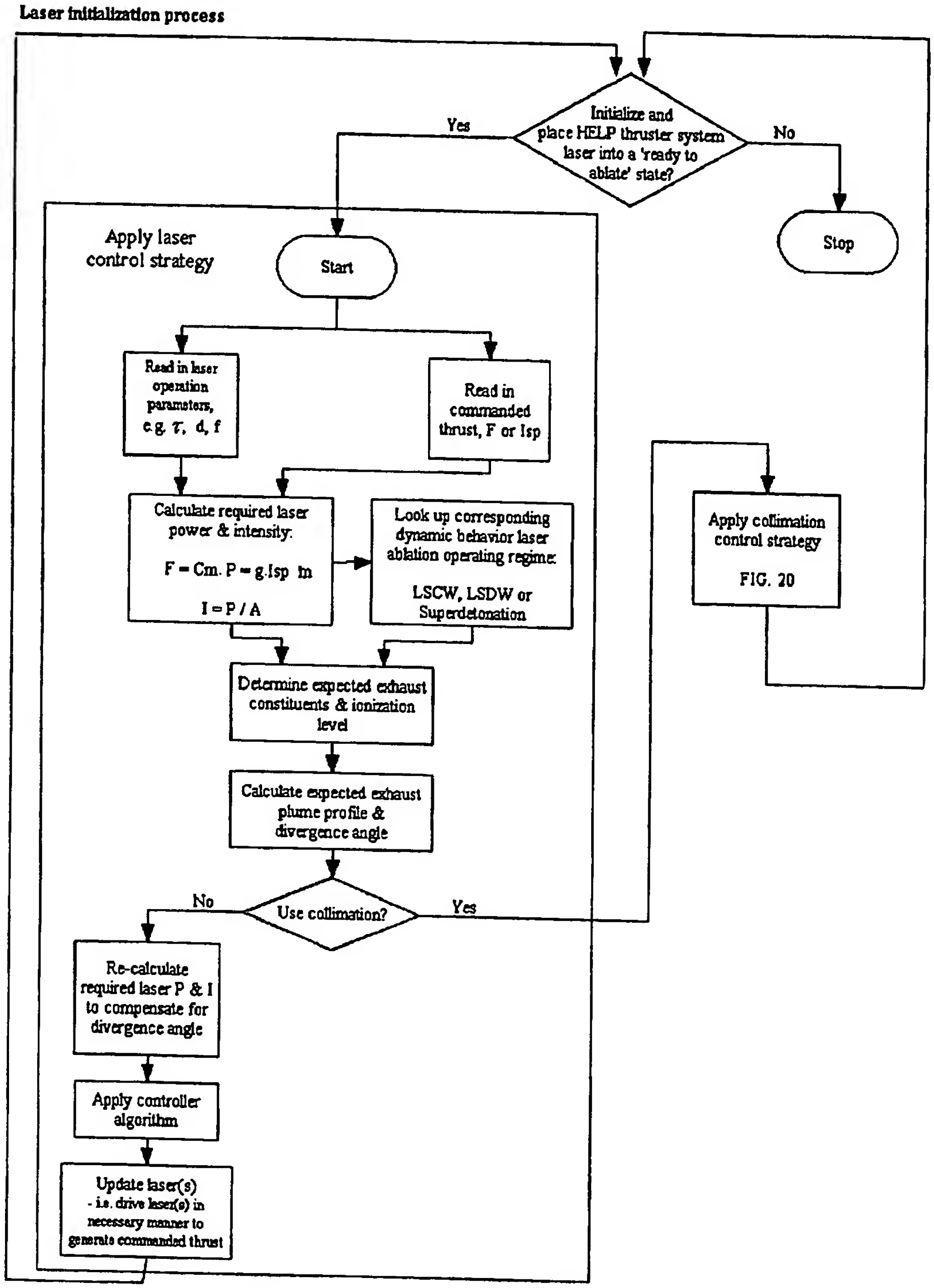


Figure 14 "Flowchart illustrating the process involved to initialize and place a laser into a 'ready to ablate' state for use within the HELP thruster system"

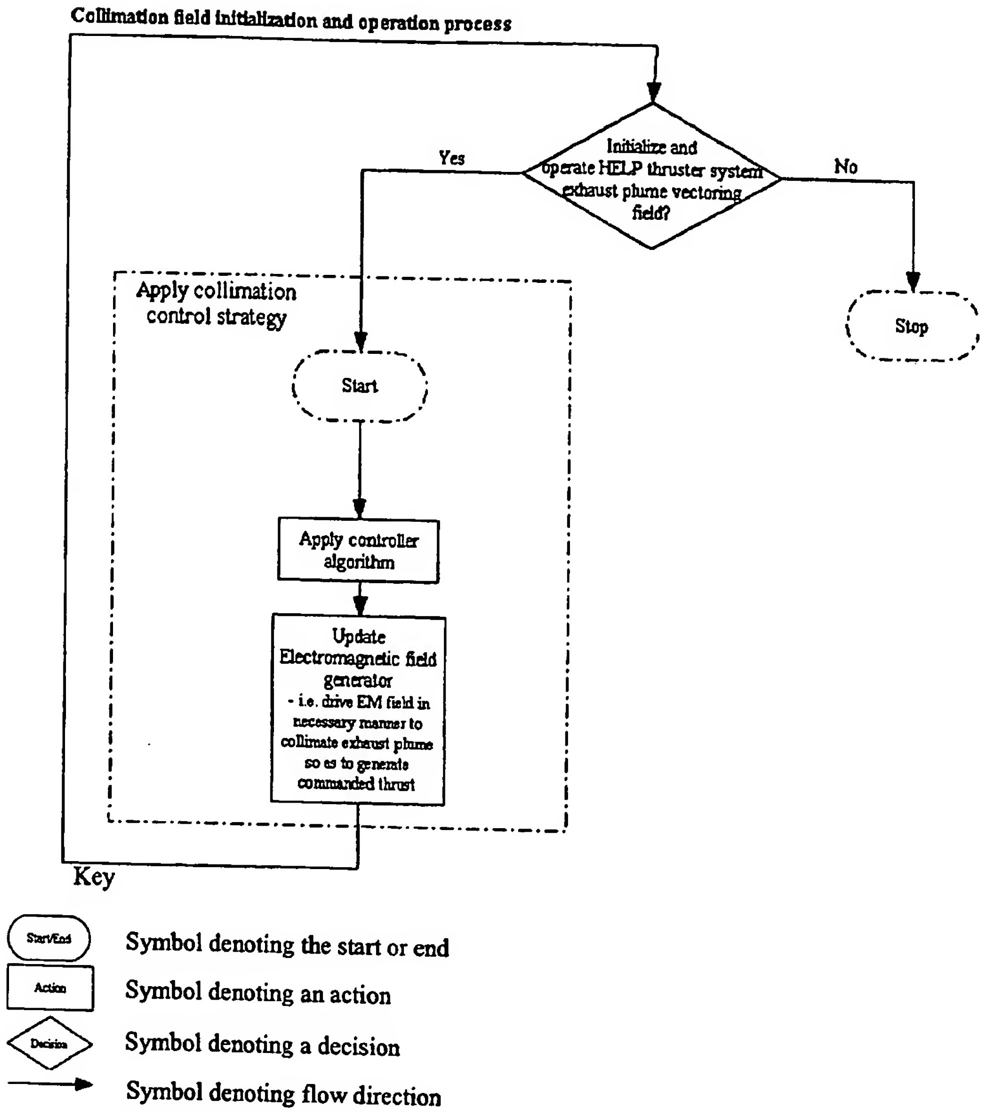


Figure 15 "Flowchart illustrating the process involved to initialize and operate the exhaust plume vectoring field for use within the HELP thruster system"

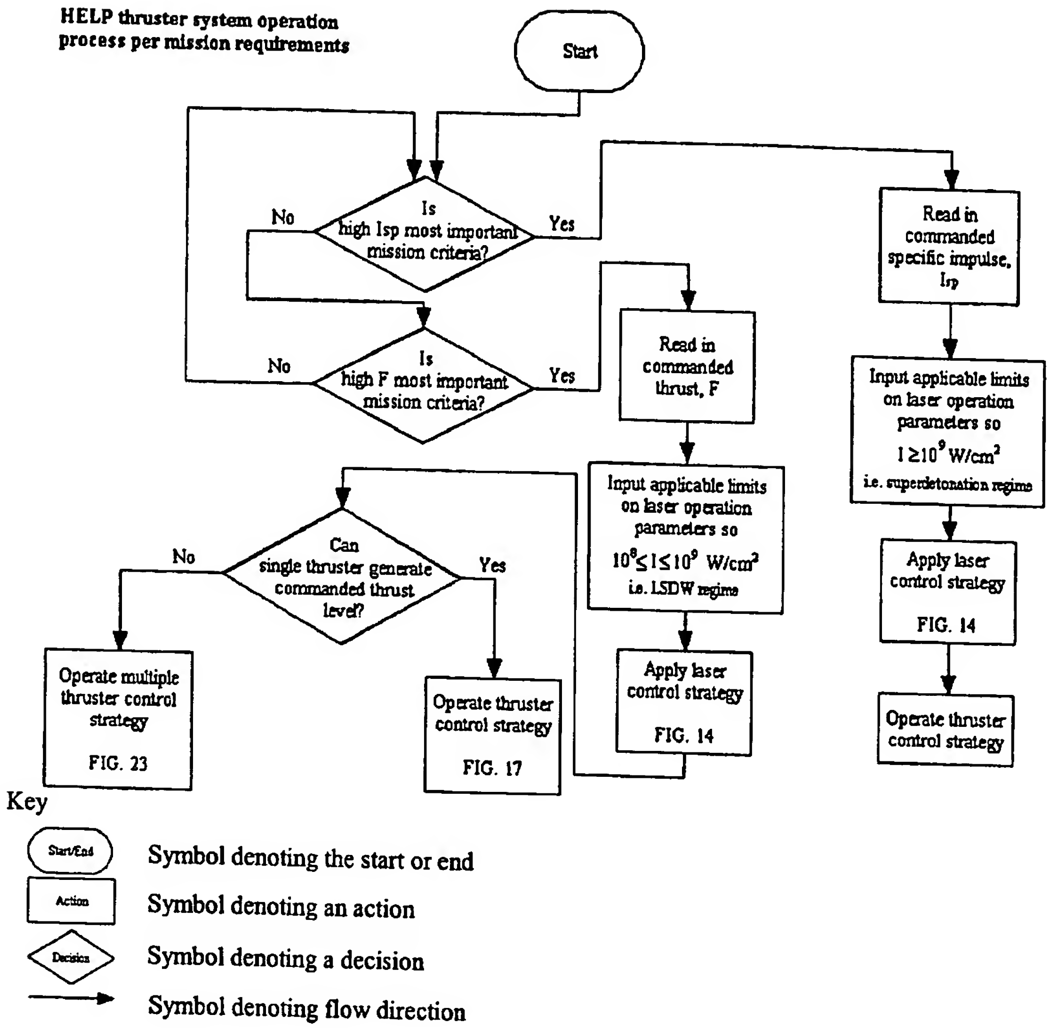


Figure 16 "Flowchart illustrating the steps involved in determining the HELP thruster system operation process per mission criteria"

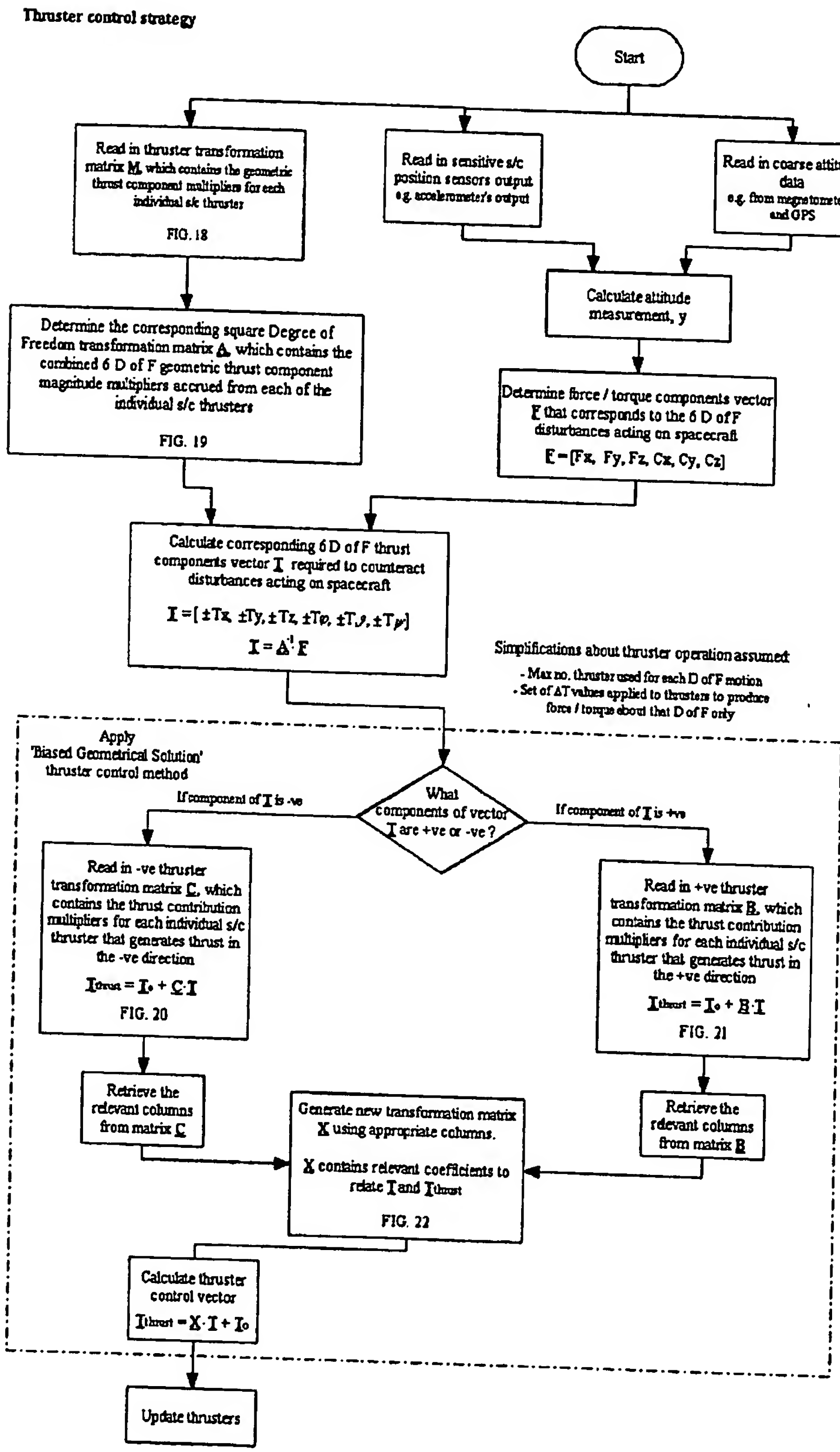


Figure 17 "Flowchart summarizing the steps of the thruster control strategy and how the thruster control vector $\underline{T}_{thrust}$, is determined"

F = **M** * **T**$_{thrust}$

F	**M**												**T**$_{thrust}$
F_x	cos70°	cos70°	cos70°	0	cos20°* cos30°	-cos20°* cos30°	-cos70°	-cos70°	-cos70°	0	-cos20°* cos30°	cos20°* cos30°	T_1
F_y	0	cos20°* cos30°	-cos20°* cos30°	-cos70°	-cos70°	-cos70°	0	-cos20°* cos30°	cos20°* cos30°	cos70°	cos70°	cos70°	T_2
F_z =	cos20°	-cos20°* cos60°	-cos20°* cos60°	cos20°	-cos20°* cos60°	-cos20°* cos60°	cos20°	-cos20°* cos60°	-cos20°* cos60°	cos20°	-cos20°* cos60°	-cos20°* cos60°	T_3
C_ϕ	0	0	0	-cos20°*D	-cos20°* cos60°*D	cos20°* cos60°*D	0	0	0	cos20°*D	-cos20°* cos60°*D	-cos20°* cos60°*D	T_4
C_θ	-cos20°D	cos20°* cos60°	cos20°* cos60°*D	0	0	0	cos20°*D	- cos20°* cos60°*D	-cos20°* cos60°*D	0	0	0	T_5
C_ψ	0	cos20°* cos30°*D	cos20°* cos30°*D	0	cos20°* cos30°*D	-cos20°* cos30°*D	0	cos20°* cos30°*D	-cos20°* cos30°*D	0	cos20°* cos30°*D	-cos20°* cos30°*D	T_6
													T_7
													T_8
													T_9
													T_{10}
													T_{11}
													T_{12}

Where

F = Force
C = Torque
T = Thrust

Figure 18 "Example of a 12×6 thruster transformation matrix M"

$\underline{F}$ = $\underline{A}$ * $\underline{T}$

F	A						T
F_x	(3cos70°+ 2cos20°*cos30°)	0	0	0	0	0	T_x
F_y	0	(3cos70°+ 2cos20°*cos30°)	0	0	0	0	T_y
F_z =	0	0	(4cos20°)	0	0	0	T_z
C_ϕ	0	0	0	(2cos20°*D+ 2cos20°* cos60°*D)	0	0	T_ϕ
C_θ	0	0	0	0	(2cos20°*D+ 2cos20°*cos60°*D)	0	T_θ
C_ψ	0	0	0	0	0	(4cos20°* cos60°*D)	T_ψ

Figure 19 "Example of 6×6 Degree of Freedom thrust transformation matrix $\underline{A}$"

$\underline{T}_{thrust}$ = $\underline{C}$ * $\underline{T}$ + $\underline{T}_o$

$\underline{T}_{thrust}$	C						T		Bias thrust $\underline{T_o}$
	x	y	z	ϕ	θ	ψ			T_o
T_1	0	0.5	0	0	2	1	$-T_x$		1
T_2	0	0	1	0.5	0	0	$-T_y$		1
T_3	0	1	1	0.5	0	1	$-T_z$		1
T_4	0.5	1	0	2	0	0	$-T_\phi$		1
T_5	0	1	1	0	0.5	0	$-T_\theta$		1
T_6 =	1	1	1	0	0.5	1	$-T_\psi$	+	1
T_7	1	0.5	0	0	0	1			1
T_8	1	1	1	0.5	1	0			1
T_9	1	0	1	0.5	1	1			1
T_{10}	0.5	0	0	0	0	0			1
T_{11}	1	0	1	1	0.5	0			1
T_{12}	0	0	1	1	0.5	1			1

Figure 20 "Example of 12×6 –ve thruster transformation matrix $\underline{C}$ in terms of negative thrust components and Degrees of Freedom"

$$\underline{T}_{thrust} = \underline{B} * \underline{T} + \underline{T}_o$$

$\underline{T}_{thrust}$	$\underline{B}$						$\underline{T}$		Bias thrust $\underline{T}_o$
	x	y	z	φ	θ	ψ			T_o
T_1	1	0.5	1	0	0	1	T_x		1
T_2	1	1	0	0.5	1	1	T_y		1
T_3	1	0	0	0.5	1	0	T_z		1
T_4	0.5	0	1	0	0	0	T_ϕ		1
T_5	1	0	0	1	0.5	1	T_θ		1
T_6 =	0	0	0	0.5	0.5	0	T_ψ	+	1
T_7	0	0.5	1	0	2	1			1
T_8	0	0	0	0.5	0	1			1
T_9	0	1	0	0.5	0	0			1
T_{10}	0.5	1	1	2	0	0			1
T_{11}	0	1	0	0	0.5	1			1
T_{12}	1	1	0	0	0.5	0			1
									1

Figure 21 "Example of 12×6 +ve thruster transformation matrix $\underline{B}$ in terms of positive thrust components and Degrees of Freedom"

$$\underline{T}_{thrust} = \underline{X} * \underline{T} + \underline{T}_o$$

$\underline{T}_{thrust}$	$\underline{X}$						$\underline{T}$		Bias thrust $\underline{T}_o$
	x	y	z	φ	θ	ψ			T_o
T_1	0	0	0	0	0	0	$-T_x$		1
T_2	0	0	0	0	0	0	$-T_y$		1
T_3	0	0	0	0	0	0	$-T_z$		1
T_4	0.5	0	0	0	0	0	$-T_\phi$		1
T_5	0	0	0	0	0	0	$-T_\theta$		1
T_6 =	1	0	0	0	0	0	$-T_\psi$	+	1
T_7	1	0	0	0	0	0			1
T_8	1	0	0	0	0	0			1
T_9	1	0	0	0	0	0			1
T_{10}	0.5	0	0	0	0	0			1
T_{11}	1	0	0	0	0	0			1
T_{12}	0	0	0	0	0	0			1
									1

Figure 22 "Example of 12×6 thruster transformation matrix $\underline{X}$"

Multiple thruster control strategy

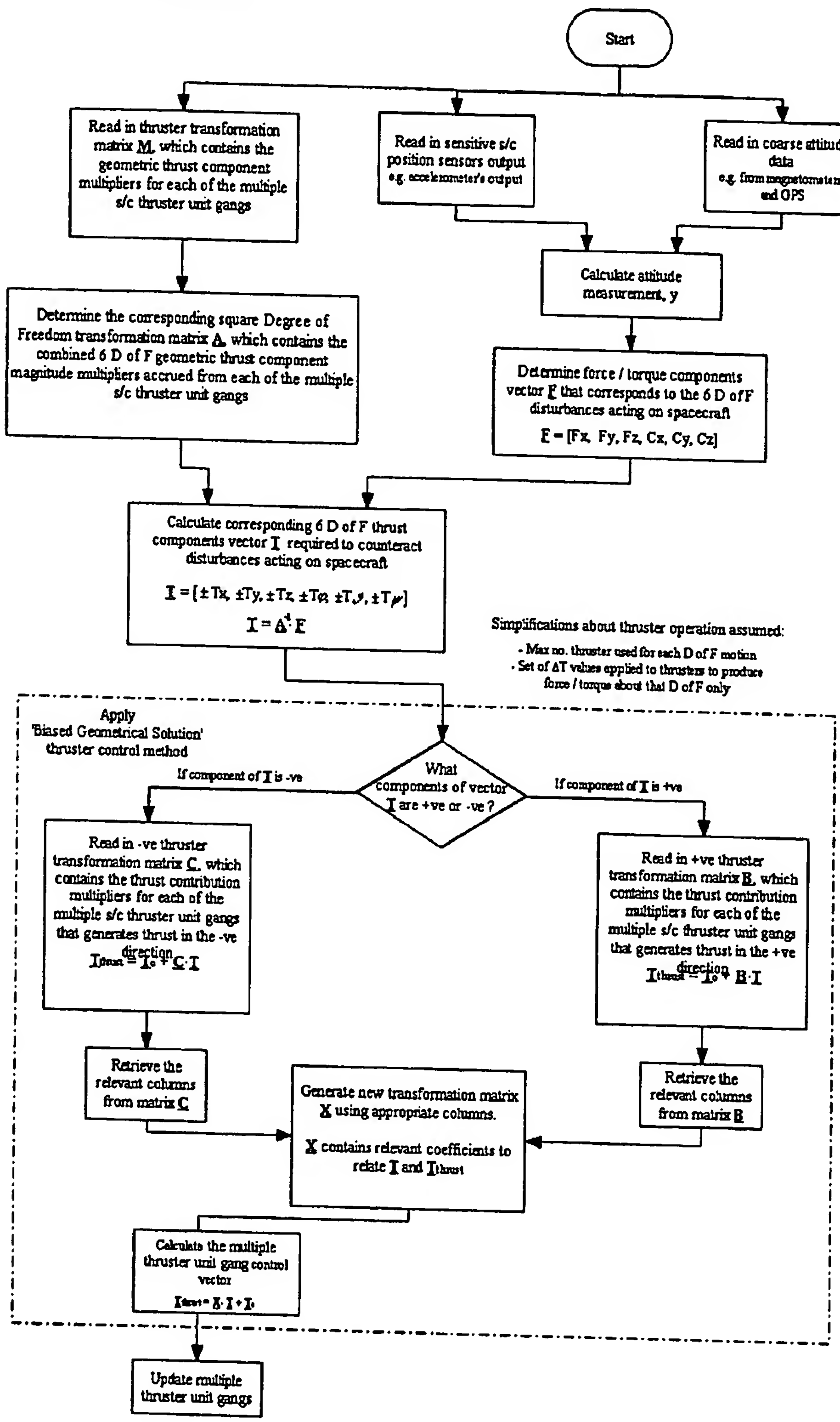


Figure 23 "Flowchart summarizing the steps of the multiple thruster control strategy and how the thruster control vector $\underline{T}_{thrust}$, is determined"

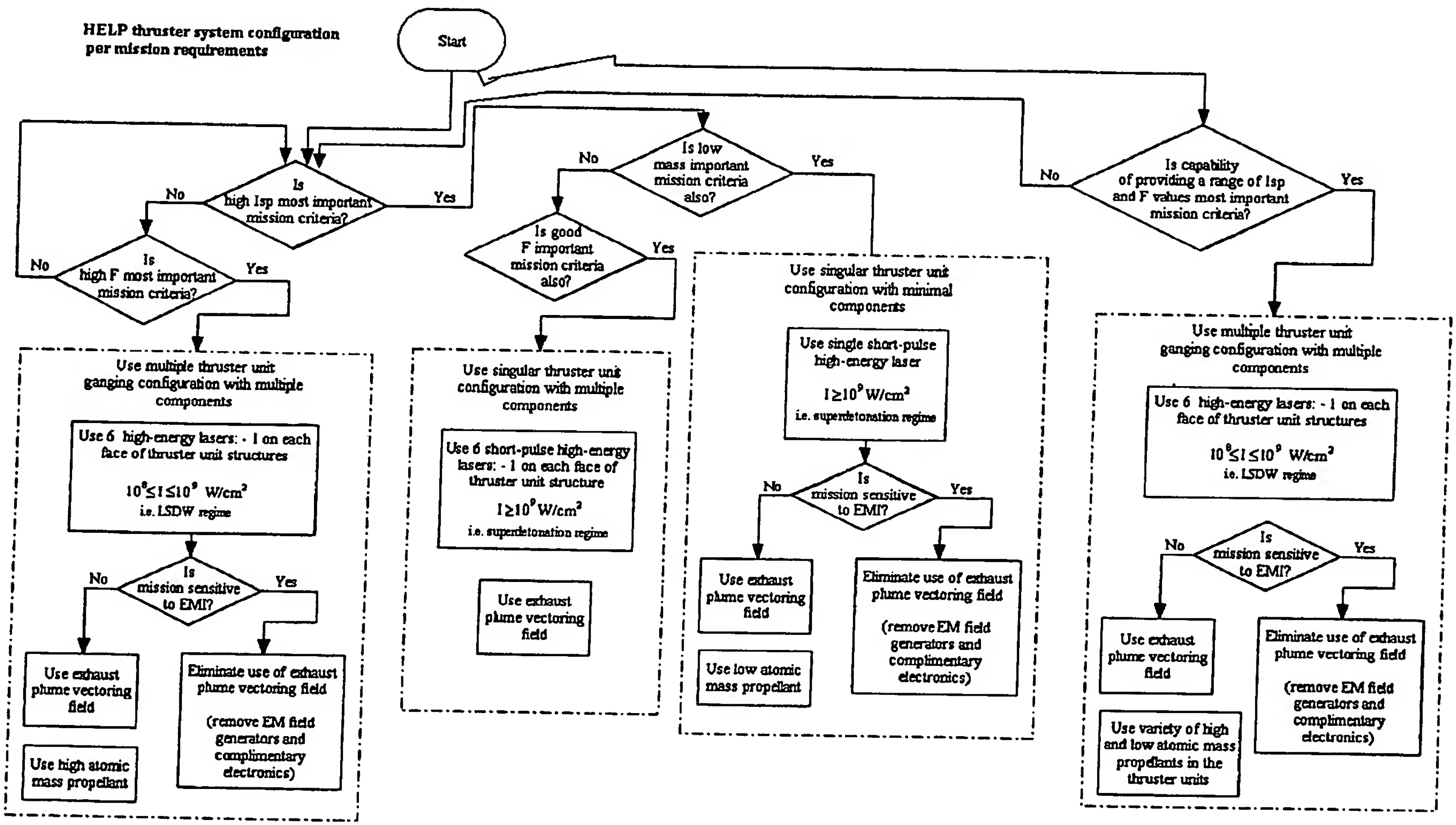


Figure 24 "Flowchart illustrating the steps involved in determining the HELP thruster system configuration & propellant choice per mission criteria"

PTO/SB/16 (05-03)
Approved for use through 4/30/2003. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53 (c).

Express Mail Label No. EV 203526025 US

17507 U.S. PTO
60/482601
06/25/03

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
Rachel	Leach	Littleton, Colorado
Gerald B.	Murphy	Littleton, Colorado

☒ *Additional inventors are being named on the* 1 *separately numbered sheets attached hereto*

TITLE OF THE INVENTION (500 characters max)

LOW IMPEDANCE TEST FIXTURE FOR IMPEDANCE MEASUREMENTS

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ENCLOSED APPLICATION PARTS *(check all that apply)*

☒ Specification *Number of Pages* 14

☒ Drawing(s) *Number of Sheets* 18

☐ Application Data Sheet. See 37 CFR 1.76

☐ CD(s), Number

☒ Other (specify) 34 Pages of Appendix A; 43 pages of Appendix B; Certificate of Mailing, and Return Postcard

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☒ Applicant claims small entity status. See 37 CFR 1.27.

☒ A check or money order is enclosed to cover the filing fees

☐ The Director is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number: 12-0600

☐ Payment by credit card. Form PTO-2038 is attached.

FILING FEE AMOUNT ($) 80

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☒ No.

☐ Yes, the name of the U.S. Government agency and the Government contract number are: _____.

[Page 1 of 1]

Respectfully submitted,
SIGNATURE [signature] Date 6-25-03

TYPED or PRINTED NAME Curtis A. Vock REGISTRATION NO. *(if appropriate)* 38,356

TELEPHONE (720) 931-3000 Docket Number: 411031

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

PROVISIONAL APPLICATION COVER SHEET
Additional Page

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Docket Number	411101

INVENTOR(S)/APPLICANT(S)

Given Name (first and middle [if any])	Family or Surname	Residence (City and either State or Foreign Country)
Thomas S.	Adams	Littleton, Colorado

Number 1 of 1

WARNING: Information on this form may become public. Credit card information should not be included on this form. Provide credit card information and authorization on PTO-2038.

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U.S. Patent and Trademark Office: U.S. DEPARTMENT OF COMMERCE

FEE TRANSMITTAL for FY 2003

Effective 01/01/2003. Patent fees are subject to annual revision.

☒ Applicant claims small entity status. See 37 CFR 1.27

TOTAL AMOUNT OF PAYMENT ($) 80

Complete if Known	
Application Number	Unknown
Filing Date	(Herewith)
First Named Inventor	Rachel Leach et al.
Examiner Name	Unknown
Art Unit	Unknown
Attorney Docket No.	411101

METHOD OF PAYMENT (check all that apply)

☒ Check ☐ Credit card ☐ Money Order ☐ Other ☐ None

☐ Deposit Account:

Deposit Account Number: 12-0600

Deposit Account Name: Lathrop & Gage L.C.

The Director is authorized to: *(check all that apply)*
☐ Charge fee(s) indicated below ☒ Credit any overpayments
☐ Charge any additional fee(s) during the pendency of this application
☐ Charge fee(s) indicated below, except for the filing fee
to the above-identified deposit account.

FEE CALCULATION

1. BASIC FILING FEE

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description	Fee Paid
1001	750	2001	375	Utility filing fee	
1002	330	2002	165	Design filing fee	
1003	520	2003	260	Plant filing fee	
1004	750	2004	375	Reissue filing fee	
1005	160	2005	80	Provisional filing fee	80

SUBTOTAL (1) ($) 80

2. EXTRA CLAIM FEES

			Extra Claims		Fee from below		Fee Paid
Total Claims		-20 ** =	0	X		=	0
Independent Claims		-3 ** =	0	X		=	0
Multiple Dependent				X		=	0

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description
1202	18	2202	9	Claims in excess of 20
1201	84	2201	42	Independent claims in excess of 3
1203	280	2203	140	Multiple dependent claim, if not paid
1204	84	2204	42	** Reissue independent claims over original patent
1205	18	2205	9	** Reissue claims in excess of 20 and over original patent

SUBTOTAL (2) ($) 0

***or number previously paid, if greater; For Reissues, see above*

FEE CALCULATION (continued)

3. ADDITIONAL FEES

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description	Fee Paid
1051	130	2051	65	Surcharge - late filing fee or oath	
1052	50	2052	25	Surcharge - late provisional filing fee or cover sheet.	
1053	130	1053	130	Non-English specification	
1812	2,520	1812	2,520	For filing a request for reexamination	
1804	920*	1804	920*	Requesting publication of SIR prior to Examiner action	
1805	1,840*	1805	1,840*	Requesting publication of SIR after Examiner action	
1251	110	2251	55	Extension for reply within first month	
1252	410	2252	205	Extension for reply within second month	
1253	930	2253	465	Extension for reply within third month	
1254	1,450	2254	725	Extension for reply within fourth month	
1255	1,970	2255	985	Extension for reply within fifth month	
1401	320	2401	160	Notice of Appeal	
1402	320	2402	160	Filing a brief in support of an appeal	
1403	280	2403	140	Request for oral hearing	
1451	1,510	1451	1,510	Petition to institute a public use proceeding	
1452	110	2452	55	Petition to revive – unavoidable	
1453	1,300	2453	650	Petition to revive – unintentional	
1501	1,300	2501	650	Utility issue fee (or reissue)	
1502	470	2502	235	Design issue fee	
1503	630	2503	315	Plant issue fee	
1460	130	1460	130	Petitions to the Commissioner	
1807	50	1807	50	Processing fee under 37 CFR 1.17 (q)	
1806	180	1806	180	Submission of Information Disclosure Stmt	
8021	40	8021	40	Recording each patent assignment per property (times number of properties)	
1809	750	2809	375	Filing a submission after final rejection (37 CFR § 1.129(a))	
1810	750	2810	375	For each additional invention to be examined (37 CFR § 1.129(b))	
1801	750	2801	375	Request for Continued Examination (RCE)	
1802	900	1802	900	Request for expedited examination of a design application	

Other fee (specify) _____

*Reduced by Basic Filing Fee Paid

SUBTOTAL (3) ($) 0

SUBMITTED BY

				Complete *(if applicable)*	
Name (Print/Type)	Curtis A. Vock	*Registration No. Attorney/Agent)*	38,356	*Telephone*	(720) 931-3000
Signature	Curtis A. Vock			*Date*	6-25-03

Practitioner's Docket No. 411101

PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of:	Rachel Leach et al.		
Application No.:	Not Assigned	Group No.:	Unknown
Filed:	Herewith	Examiner:	Unknown

FOR: HYBRID ELECTRIC-LASER PROPULSION SYSTEM AND ASSOCIATED METHODS

MS PROVISIONAL PATENT APPLICATION
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

EXPRESS MAIL CERTIFICATE

"Express Mail" label number EV 203526025 US
Date of Deposit: 25 June 2003

I hereby state that the following *attached* papers

1. Provisional Application for Patent Cover Sheet (2 pages);
2. Fee Transmittal Sheet (1 page);
3. Specification, including 3 pages of claims and 34 pages of Appendix A, (48 pages of Claims);
4. Appendix B + 1 cover sheet (43 pages)
5. Drawings, Fig. 1- 24 (18 sheets);
6. Check in the amount of $80.00;
7. Certificate of Mailing, and
8. Return Postcard.

are being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10, on the date indicated above and is addressed to: MS Provisional Patent Application, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.

Heather Fedor

Heather Fedor